

# **Human Bioresponse to Low-Frequency Underwater Sound**

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## **LONG-TERM GOALS**

The ultimate goal of our research is to provide a physiologically and acoustically based prediction of human lung damage due to low-frequency underwater sound. The threshold curve will indicate the acoustic pressure at which damage may occur as a function of frequency. The results we produce will aid other members of the research team in determining whether the sound pressure levels produced or predicted using various sources in various situations are adequate to function as a nonlethal diver deterrent.

## **OBJECTIVES**

The first objective is to determine how the human body responds to low-frequency underwater sound and what causes the hemorrhaging in the lungs, which is commonly the injury that is first encountered. The second objective is to use this understanding of lung damage to create a damage threshold curve which indicates the predicted acoustic pressure, as a function of frequency, below which injury may be avoided.

## **APPROACH**

A finite element model of human thorax has been created that includes idealized geometrical representations of the lungs, ribs, trachea, bronchiole tubes, spine, sternum, and a generalized “abdominal mass” which accounts for the diaphragm, stomach, kidneys, and spleen. The elastic properties of the lungs are calculated using a micromechanical model that accounts for the internal dynamics of individual alveoli and then takes a spatial average that determines the elastic moduli for the corresponding effective continuous medium. The resulting finite-element model of the effective medium then calculates the response of the lung and other peripheral organs to low-frequency underwater sound, with a focus on lung surface displacement, shear stress and shear strain. Performing a series of simulations over a range of frequencies allows for the determination of the acoustic pressure required to cause a shear strain equal to that believed to be the threshold level for damage in the lungs. The team members on this project are:

Mark F. Hamilton, Professor and Principal Investigator

Yurii A. Ilinskii, Senior Research Scientist

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## WORK COMPLETED

An investigation into the feasibility of using MRI-based finite element meshes of the organs in COMSOL was performed with the assistance of COMSOL technical support.

A simpler, idealized geometrical representation has been completed which includes the lungs, trachea, bronchiole tubes, heart, ribs, sternum, spine, diaphragm, stomach, kidneys and spleen. The specific shapes and sizes of the bones and airways have been modified in a way such that the meshing software included in COMSOL produces high quality, computationally efficient meshes. The model, which has two-fold symmetry, was then divided into quadrants and only one of the quadrants was used for the simulations.

A COMSOL finite-element model was created using the acoustics module coupled to either the partial differential equation module or the structural mechanics module. The two methods were shown to be in excellent agreement, and the structural mechanics module was chosen due to its ability to exploit geometric symmetries and efficiently calculate stress and strain throughout all material domains.

The various linear solvers included with COMSOL were tested and it was concluded that the PARDISO solver was the most computationally efficient.

Simulations were performed that investigated how gravity and diver orientation affect the response of the lung to low-frequency underwater sound. Gravity can cause the lungs to be stressed inhomogeneously, which makes the lung density and elastic properties spatially dependent.

Simulations were performed using the thoracic model scaled to that of a mouse in order to compare our numerical results to laboratory experiments on mice and rats by Diane Dalecki's group at the University of Rochester Center for Biomedical Ultrasound. Similar tests were performed in COMSOL with the human-scaled thoracic model using a large range of incident frequencies. Also, an investigation of the influence of quality factor on the induced surface displacement and shear stress and shear strain was performed.

Finally, a preliminary elasto-plastic model of lung damage was created in COMSOL. It is intended to act as a model of progressive lung damage due to low-frequency underwater sound.

## RESULTS

The investigation of the effects of gravity on the response of the human lung in an upright position has shown that although there is a small shift in the resonance frequency of the lung, the effect is relatively minor. Furthermore, when a human is in the prone position, such as when one is swimming, the effect is further diminished.

It was concluded that for this investigation, using the available MRI-based meshes, COMSOL cannot properly import, preprocess, and perform simulations with reasonable efficiency. The amount of

memory and computational time required, if the meshes can be imported at all, is prohibitively large. For this reason, a simplified geometrical model was used in all subsequent calculations.

The utilization of the structural mechanics module and our simplified geometrical model allowed us to exploit the symmetry of the model and solve the problem over only one quarter of the geometry. This modification in geometry resulted in significantly decreased solution time and memory requirements. With this new model, the mesh resolution can be much higher than the old model while using the same amount of memory.

For a mouse-scaled thoracic model, a 2 kPa total acoustic pressure was generated at the surface of the lung and the resulting maximum shear strain was calculated to be approximately 0.2. The Dalecki group has previously stated that 2 kPa is the threshold pressure for damage in mice, so this shear strain value is taken as the preliminary threshold value for mice and also humans.

A widely varying quality factor for human lung has been given in the literature, and the impact of this has been calculated. For values of the quality factor varying between 1.8 and 4.9, as reported in the literature, the calculated shear strain varies from 0.13 to 0.32. In the subsequent calculations a quality factor of 2 was used, which is based on what we believe is the most reliable data.

A plot of the preliminary results showing the acoustic pressure required for an induced shear strain of 0.2 was calculated for humans. The slope of this curve above resonance shows reasonable agreement with the slope of the damage threshold plot that Dalecki's group has produced for mice.

## **IMPACT/APPLICATIONS**

For development of non-lethal methods of swimmer neutralization based on low-frequency underwater sound, our research will help estimate acoustic thresholds below which serious or fatal injuries may be avoided. In addition, this finite element thoracic model may also be useful for a variety of other applications including simulation of human lung response to blast waves and comparison of lung dynamics in health and disease.

## **PUBLICATIONS (MEETING ABSTRACTS)**

M. S. Wochner, Y. Zhang, Yu. A. Ilinskii, M. F. Hamilton, and E. A. Zabolotskaya, "Influence of inhomogeneity and geometry on lung response to low-frequency underwater sound," *J. Acoust. Soc. Am.* **122**, 2957(A) (2007).

M. S. Wochner, Yu. A. Ilinskii, M. F. Hamilton, and E. A. Zabolotskaya, "Simulated response of the human lung to low-frequency underwater sound using a finite-element-based thoracic model," *J. Acoust. Soc. Am.* **123**, 3914(A) (2008).

S. Gourlie and M. F. Hamilton, "Henning von Gierke's continuing contribution: Underwater whole-body vibration," *J. Acoust. Soc. Am.* **123**, 3132(A) (2008).

## **HONORS/AWARDS/PRIZES**

Sarah Gourlie, an M.S. student at The University of Texas at Austin who was supported on this project and whose thesis (August 2008) is entitled “Whole-Body Vibration of Humans Due to a Low-Frequency Underwater Sound Field,” received the Best Student Paper Award from the Technical Committee on Noise at the Spring 2008 Meeting of the Acoustical Society of America in Paris, France.